Renewable and Sustainable Energy Reviews 16 (2012) 170–177

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Net energy analysis of domestic solar water heating installations in operation

Patxi Hernandez [a,b,*], Paul Kenny [c]

[a] UCD Energy Research Group, University College Dublin, Belfield, Dublin 4, Ireland
[b] TECNALIA, Barrio Lasao, Azpeitia, Gipuzkoa, Spain
[c] UCD School of Architecture, Landscape & Civil Engineering, Belfield, Dublin 4, Ireland

ARTICLE INFO

Article history:
Received 11 May 2011
Accepted 5 July 2011
Available online 14 September 2011

Keywords:
Net energy
Life cycle energy
Domestic solar water heating
Embodied energy
Energy payback

ABSTRACT

The potential of solar water heating systems to reduce domestic energy use is frequently acknowledged. However there are two factors that are rarely discussed when studying this technology. Firstly the real performance of the installed systems in operation, and secondly a life cycle perspective of its energy use. These two issues are reviewed in this paper, and a field study in Ireland is also presented. In the review, some studies show that measured real performance of domestic solar water heating systems can be lower than expectations. Concerning their life cycle energy performance, existing studies show that the initial energy investment for the systems (their embodied energy) is a small portion of the energy savings over their lifetime with calculation paybacks generally lower than 2 years. On the field study carried in Ireland, representative of a maritime north European climate, the 'energy payback' based on the expected energy savings is between 1.2 and 3.5 years, values comparable to previous studies considering the less favourable climate and installation characteristics. However the measured energy savings generally worsened the life cycle energy performance of this technology and thus increased the energy payback period. The study concludes that while there is a real potential for life cycle energy savings through domestic solar water heating installations, devising mechanisms to ensure proper design, installation and operation of systems is essential for this technology.

Contents

1. Introduction: the potential of domestic solar water heating

Energy consumption in residential buildings represents a large portion of global energy use, approximately 25% of total primary energy use in the European Union [1]. Water heating was responsible for around a quarter of that energy use [2]. Domestic Solar Water Heating (DSWH) is a well proven technology used to reduce the energy demand for providing domestic hot water, and its potential to largely reduce domestic energy use is frequently acknowledged [3–6].

Building regulations and standards are progressively introducing the use of renewable energy systems and in particular solar water heating systems, and the market for solar thermal collectors is steadily growing. The number of yearly installations increased threefold in Europe in the ten years to 2008 (Fig. 1).

* Corresponding author at: TECNALIA, Barrio Lasao, Azpeitia, Gipuzkoa, Spain. Tel.: +34 653749027; fax: +34 944 041 445.
E-mail addresses: patxi.hernandez@tecnalia.com, patxihi@gmail.com (P. Hernandez).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2011.07.144

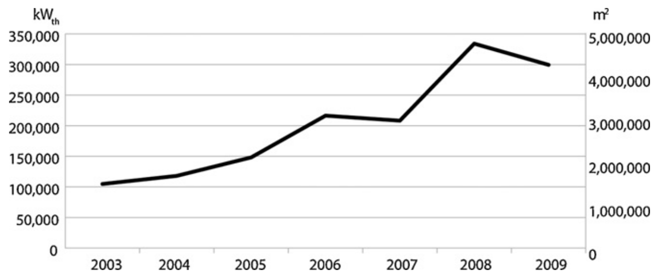


Fig. 1. Solar thermal market in EU 27 and Switzerland – glazed collectors (newly installed capacity) [43].

While these studies clearly illustrate a viable path towards the reduction of energy use and carbon emissions, there are two aspects that are frequently not considered when calculating the potential of DSWH:

Firstly, the real performance of the installations. While there has been rapid development in certification of such products and systems, their installation and operation is frequently not regulated and controlled, and the real performance of the installations is not well documented.

Secondly, the embodied energy and resources associated with the production, installation, and maintenance of a DSWH system. While this aspect is considered in research, it is rarely considered in policy or in practice.

This paper briefly reviews the methods used to both calculate and measure energy performance, and existing studies including information on life cycle, embodied energy and 'net energy' performance of DSWH. Secondly a life cycle energy analysis or 'net energy analysis' for six DSWH in Ireland is performed, looking at the life cycle energy performance through the 'energy payback' and 'Net Energy Ratio' indicators, based on both the expected and measured performance of the systems.

2. Review of DSWH systems performance – from theory to practice

2.1. Calculating energy performance

There are multiple calculation methods and tools available to size and estimate the energy performance of solar systems. These include from simple rules of thumb to computer software such as TRNSYS [7], POLYSUN [8] or TSOL [9] where installation details can be input and performance of the systems calculated in detail, including dynamic energy performance at short time intervals. There are also intermediate complexity or simplified calculation methods such as those implemented in EN 15316-4-3:2007 [10], or described by various authors [11–13]. These methods generally contain various simplifications, both for climate and for the efficiency of system components, but can generally provide sufficient detail for an adequate sizing and for a calculation of monthly collected solar energy (solar output) of DSWH installations.

The minimum information requirements for calculation methods are typically the following:

- *Solar irradiation on the collection plane*: Monthly horizontal irradiation values are generally sufficient for simplified methods, and irradiation values on the collection plane can be calculated based the orientation and slope of the solar collectors.
- *Collector loop efficiency*: The efficiency of the collector loop is also an input in calculation methods, with the level of detail depending on the method. In most cases, the information requirement is reduced to the efficiency of the solar collectors for which standard values can be used for both flat plate and evacuated tube systems.
- *Storage tank size and losses*: The size of the associated water storage vessel is required as an input in all methods. Additional inputs that may be required by some calculation methods include the position (horizontal or vertical), insulation levels and controls.
- *Circulation system*: DSWH systems can be thermoshipon or forced circulation. The pump wattage and its annual electricity use can be specified or estimated based on the collectors' area.
- *Hot water demand profile*: The profile of hot water demand is an important element of calculation methods. For simplified methods the domestic hot water demand can be estimated based on, for example, the dwelling characteristics and number of expected occupants.

2.2. Monitoring energy performance

The performance of solar thermal systems and their components is now routinely tested according to standards such as EN 12975 for solar collectors [14], or EN 12976 for factory made systems [15]. The testing and monitoring of 'custom built' systems, which are assembled from a number of different components, is not so widespread but standards such as ISO 9469 [16] and draft CEN 12977 [17] also define a procedure for testing performance. All testing is carried under standard conditions, either indoor or outdoor. It calculates the performance of the systems and components in detail, with the possibility of testing different heat demand profiles and system characteristics. Validated simulation tools can also aid in the evaluation of the performance under a wider range of operational factors than the particular testing conditions.

The results of these laboratory tests are frequently used as inputs in simplified calculation methods to predict performance or the sizing of solar installations. However, some differences between measured and calculated performance can be expected in the operation of solar systems. These are typically due to specific usage characteristics and demand profiles, installation characteristics and control, maintenance factors and potential operational problems.

Monitoring the operation of large solar water heating installations is quite common, sometimes as part of an energy service company (ESCO) contract or as an instrument to implement 'guaranteed results' schemes and policies [18,19]. For DSWH systems, however, there is very limited data available on the real performance of installations. From the published data, Parker [20] reports good performance (when compared with expectations) of solar water heating systems that were studied as part of a large scale monitoring project. Other projects monitoring real installation do, however, show discrepancies between real measurements and expectations. Thomsen et al. [21] in a report studying energy performance of 12 demonstration low-energy buildings, found that two of the solar thermal installations presented low efficiency, one of the systems studied showing a low performance because of the simple error of a valve never being re-opened after maintenance. Wall [22] presented measured results of the energy performance of terrace houses in Sweden, showing a solar output for hot water to be nearly 30% less than expected at design stage. Lloyd and Kerr [23] showed that discrepancies between expectations and the real operation of systems are due mainly to multiple and varied reasons, depending both on the system design, installation, installer, the auxiliary supply systems, weather factors, and the water usage.

3. Review of previous net energy analysis of DSWH systems

A complete life cycle energy evaluation of a system ideally accounts for all energy inputs through its life cycle, from the extraction of materials and manufacturing process to its operation up to the end of its service life. This type of analysis is frequently referred to as 'net energy analysis', and has been applied to the

Table 1
Summary of previous life cycle energy analysis of DSWH systems.

Author	Solar collection area (m^2)	EE (MJ)	Location	Energy payback (years)
Mathur and Bansal (1999)	2	6,000	Various locations, India	0.7–4.1
Crawford and Treloar (2004)	3.8	20,000	Melbourne, Australia	0.2–2
Ardente et al. (2005)	2.13	11,500	Palermo, Italy	<2
Kalogirou (2004)	3.8	8,700	Nicosia, Cyprus	1.2
Asif et al. (2007)	1	1,700	Lahore, Pakistan	0.5
Battisti and Corrado (2005)	1.7	3,040	Rome, Italy	0.4–1.6
Kalogirou (2009)	2.7	6,946	Nicosia, Cyprus	1.1

evaluation of multiple energy systems since the 1970s, from oil and gas extraction to renewable energies. Net energy analysis compares the amount of energy delivered by a technology to the total energy required to find, extract, process, deliver, and otherwise upgrade that energy to a useful form [24].

For solar energy systems, a net energy analysis compares the embodied energy (EE) of an installation with the energy saved, which would otherwise be delivered by a different system, in most cases resulting in the combustion of a fossil fuel. The EE would ideally includes, in addition to energy associated with the materials and manufacturing of the installation, all additional energy uses related to its life cycle, including transport, maintenance, disposal, etc. A net energy analysis for DSWH systems can be performed comparing the EE with the energy saved by the solar system throughout its service life. There are a number of existing studies that present 'net energy analyses' of DSWH systems, generally expressing the results in terms of 'energy payback', which is the number of years needed for the DSWH to save as much energy as the EE of the system.

The EE is calculated based on a life cycle inventory or input–output analysis. For the calculation of the expected performance of the system and energy savings various methods are used, from basic assumptions and rules of thumb about performance, to detailed dynamic simulation of the systems.

Mathur and Bansal [25], studied a number of options for thermosyphonic systems in India and estimated circa 5800 MJ of EE for a system with 2 m^2 flat plate collector and considerably less (3776 MJ) for the system with evacuated tubes. This was based on an inventory of materials, multiplying the weight of each material for its EE, and adding the energy use during the manufacturing process to obtain total EE for the system. Comparing the calculated EE data with different solar collection outputs calculated for various locations in India, the reported 'energy payback' periods varied between 0.73 and 4.16 years, depending mostly on the location climate.

Crawford and Treloar [26] estimated EE for solar water heating systems in Australia, based on a hybrid input–output analysis, which is considered to be a more complete and accurate analysis of the systems EE. They calculated the EE of the 3.6 m^2 DSWH system to be approximately 20,000 MJ. The study estimates the solar energy collected in Melbourne, Australia, and applies the conversion factors according to the substitution of different auxiliary energy systems. They concluded that the 'energy payback' would vary between 0.5 years when solar was substituting directly for electric heating and 2 years when solar substituted for gas water heating.

Ardente et al. [27], provides a detailed life cycle analysis for a 2.13 m^2 solar water thermosyphonic system, and calculates the EE as 11,500 MJ of primary energy. The primary energy savings of the system, estimated for the city of Palermo, Italy, were 6600 MJ per year, and the energy payback was calculated at less than 2 years.

Kalogirou presents the analysis of a 3.8 m^2 pressurised DSWH system [28], calculating the EE to be 8700 MJ for the system, and of 2.8 m^2 thermoshyponic system [29], calculating the EE to be 6946 MJ.

The primary energy savings of the systems in Nicosia, Cyprus, are calculated with monthly calculation methods (TRNSYS, Polysun). The energy payback periods presented were 1.2 years for the pumped system and 1.1 years for the thermoshyponic system.

Battisti and Corrado [30] presented a detailed LCA for a thermosyphonic system with a 1.7 m^2 flat plate collector, calculating the EE to be 3040 MJ. The energy payback periods are estimated to be between 5 and 19 months depending on the energy substituted, with an estimated yearly output of 544 kWh (1958 MJ) for the system.

Asif et al. [31] compared life cycle performance of two laboratory prototypes of aluminium and stainless steel solar collectors with built-in storage. For a 1 m^2 collection area, the EE was calculated to be 1458 MJ for steel, and 2013 MJ for an aluminium system. The annual energy collected by the solar systems was estimated to 2570 and 3837 MJ respectively at Lahore, Pakistan, calculating an energy payback of between 6 and 7 months.

A summary of the previous studies is summarized in Table 1. It can be observed that these energy paybacks are generally quite short, generally below 2 years.

It should be noted that the energy payback calculations in these studies are based on estimates or predictions of the installations' performance, not on the real measured performance of the systems in operation. These studies have also been performed in climates with favourable conditions for solar water heating, with generally warm temperatures and high solar irradiation values. In the study by Mathur and Bansal [25], where different locations in India are analyzed, results show large variability in the collected solar energy and therefore a wide range of energy paybacks.

It can be expected that in climates with relatively lower solar irradiation values, such as in Northern Europe, the collected solar energy diminishes and the energy payback time increases. If the real performance of the installations also differs from the expected performance, as is found by some of the reviewed monitoring studies in Section 2.2, the results of the 'net energy analysis' and the energy payback period would also differ.

By way of illustrating the more marginal performance of DSWH systems in climates generally less favourable than those presented previously, this paper presents a 'net energy' analysis for a sample of installations in Ireland, a maritime climate with relatively lower solar irradiation levels. The study also accounts for the real monitored performance of the installations.

4. Net energy analysis of six installations in Ireland

This study analyze the performance of six DSWH systems, chosen from a pool of volunteering owners of existing installations, include different types of systems (flat plate and vacuum tubes), sizes, manufacturers and installers. Solar radiation in Ireland is significantly lower than the reviewed studies in India, Australia, Italy or Cyprus, but with approximately 1000 kWh of incident solar radiation per square meter, the radiation is comparable for example to countries in central and northern Europe (Fig. 2).

The system characteristics of the six installations analyzed are presented in Table 2. The characteristics represent those needed

Table 2
Main characteristics of DSWH installations.

System ID.	Location	Collector area (m^2)	Collector type	Orientation	Collector plane tilt angle (°)	Storage capacity (l)	Auxiliary heating type	Number of occupants
No. 1	Bray. Co. Wicklow	4.4	Flat plate	S	30	300	Condensing gas boiler	4
No. 2	Lismore, Co. Waterford	6	Flat plate	S	45	300	Ground source heat pump	4
No. 3	Lavagh, Co Sligo	2	Evacuated tube	S	40	150	Gas boiler	4
No. 4	Bandon, Co. Cork,	4.2	Flat plate	S	45	200	Wood stove and electric immersion	4
No. 5	Kenmare, Co. Kerry	4	Evacuated tube	S	30	300	Gas condensing boiler	4 (B&B)
No. 6	Clogh, Co. Kilkenny	8.1	Flat plate	SE	35	400	Ground source heat pump	5

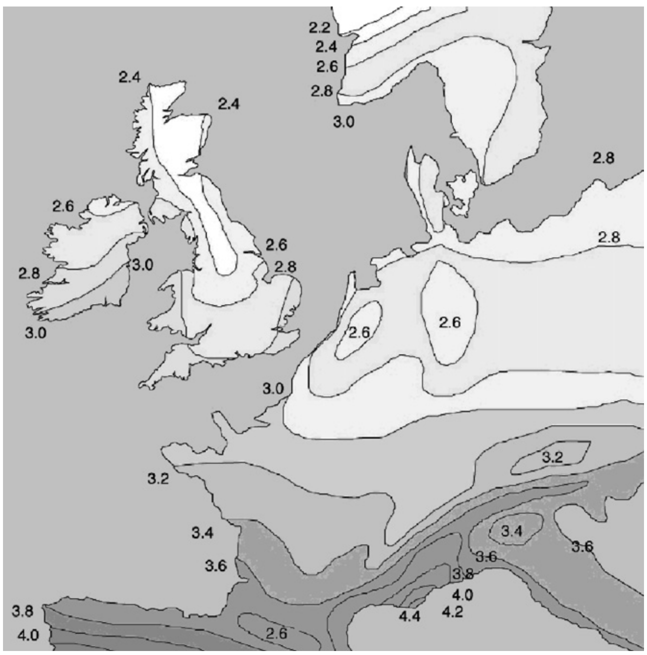


Fig. 2. Daily average solar radiation (kWh/m^2) [44].

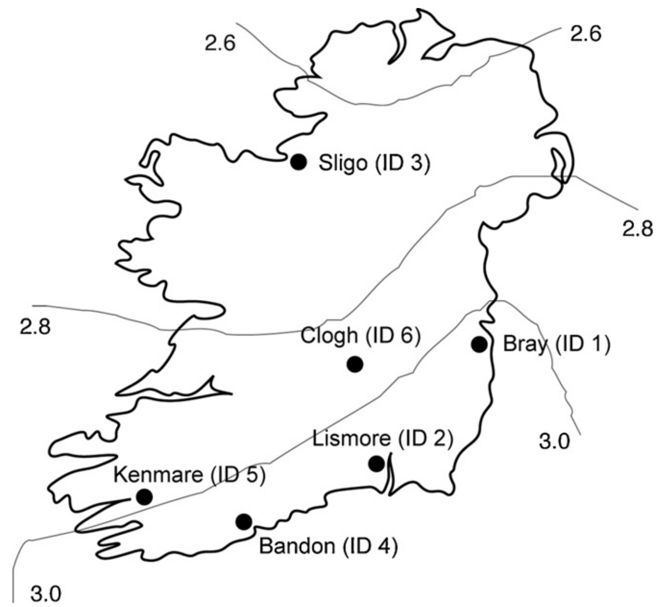


Fig. 3. Location of studied installations, and daily average solar radiation contours (kWh/m^2).

as input for the calculation of system performance using a simplified methodology such as EN 15316-4-3 [10]. A picture or the installations and their location within Ireland can be seen in Fig. 3.

4.1. Performance of the installations

The installations were monitored for a full year to record the actual energy performance. Due to the specific characteristics of each system and some project constraints, the variables measured were limited to hot water usage, collected solar energy (solar output), and solar irradiation.

For the hot water usage, the heat measurement integrated the readings from a pair Pt-100 resistance thermometers placed at the storage tank cold water inlet and hot water outlet, and an ultrasonic flow meter on the cold water inlet. Similarly, an ultrasonic flow meter was installed in the collector loop, with another pair of Pt-100 probes measuring hot and cold temperatures on the supply and return to the storage tank. All variables were measured and the energy flow calculated with a 10-s interval and with cumulative values logged every 10 min. An ISO second class pyranometer was also installed in each location to measure solar irradiation. Details on the placement of the monitoring equipment can be seen in Fig. 4.

Daily average solar irradiation for each month is shown in Fig. 5. The monthly totals for measured solar output and hot water usage are displayed in Figs. 6 and 7.

The expected performance of the installations was also calculated using the system characteristics as input and employing the simplified methodology details in EN 15316 [10]. The purpose of this calculation was to replicate calculations that were carried out at the design stage, using standard hot water usage values (40 l per day at 45°), and standard meteorological data for Ireland based on Dublin [32]. Typical values for the collector loop efficiency, storage losses, electricity use for the pump, etc. were also used. Expected annual collected solar energy output for the installations varied between 330 kWh/m^2 for installation No. 6 (largest installation with 8 m^2 of flat plate collectors) to 650 kWh/m^2 for installation No. 3 (smallest installation with 2 m^2 of evacuated tube collectors).

Table 3 displays the annual results for both the predicted and measured annual energy output.

It can be observed that the measured performance of installations No. 2 and No. 5 is better than predicted, which was due to a relatively high solar irradiation at those locations during the monitored year, to being appropriately installed and maintained, and to having a hot water demand above what was expected (particularly in installation No. 5, which operated occasionally as guest accommodation).

The rest of the installations shows a solar collection lower than expected, due to various reasons. The worst performing installation No. 6 experienced control problems, and detailed analysis of the sub-hourly monitored data showed that an installed ground source heat pump connected to the same water tank was providing

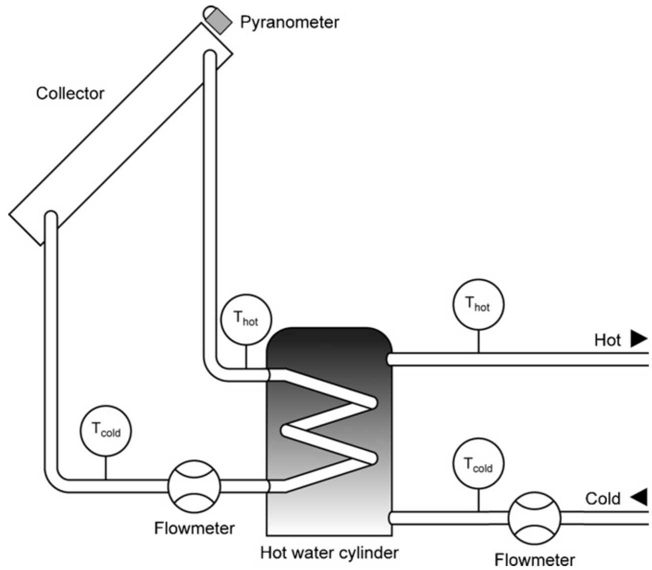


Fig. 4. Schematic diagram of the installation indicating placement of monitoring equipment.

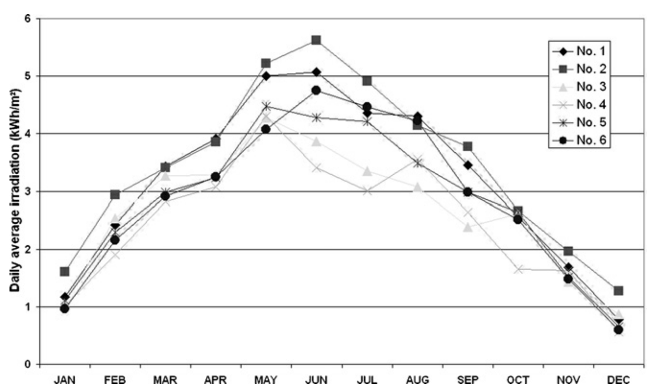


Fig. 5. Daily average solar irradiance on the collector plane at the six locations (kWh/m^2).

excessive heat and prevented the solar system from operating efficiently during most days. A similar but less severe problem was found in installation No. 2 where a heat pump was also used as an auxiliary heating system. In installation No. 3, the low system output was mainly attributed to the integration of the solar collector with the existing water tank, which was not specifically design to exploit the full potential of the solar collectors. Low performance

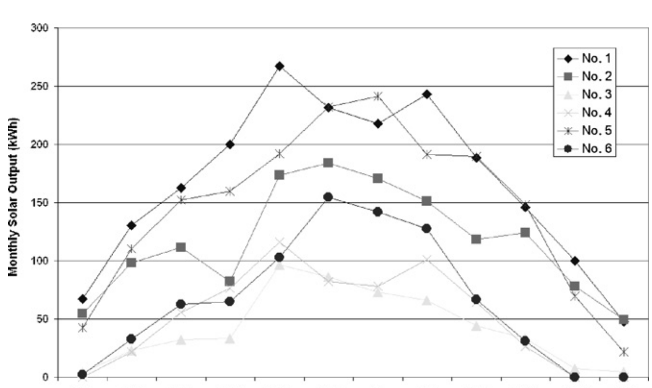


Fig. 6. Monthly collected solar energy output for the six monitored installations (kWh).

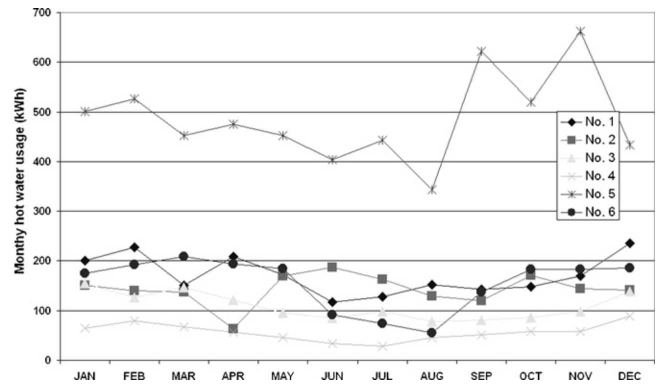


Fig. 7. Monthly hot water usage for the six monitored installations (kWh).

Table 3
Expected and measured solar energy output in kWh.

System ID	Expected output (kWh)	Measured output (kWh)	Difference measured/ expected
No. 1	1640	1778	+9%
No. 2	1829	1370	−23%
No. 3	1050	503	−52%
No. 4	1548	494	−71%
No. 5	1578	1751	+12%
No. 6	2372	686	−78%

in installation No. 4 was due to a combination of lower hot water usage, relatively low solar radiation for that year, and the occasional use of a wood boiler that overheated the tank directly affecting the performance of the solar system.

These results reflect the high potential contribution of DSWH in Ireland, with two of the installations performing very well for the monitored year and delivering a high solar output. They also demonstrate the sensitivity of solar output to various factors, such as hot water demand, use of auxiliary heating systems, and the control and maintenance of the installations. The worst performing installations highlight problems of design and control, in particular in relation to the integration of the auxiliary heating systems. These problems illustrate the importance of certification and quality control schemes for designers and installers.

4.2. Embodied energy (EE) calculations

There are many uncertainties linked to the cycle boundaries chosen for EE calculations and the availability of the data, as discussed in a review by Dixit et al. [33].

The majority of the components of the studied installations (pumps, expansion vessels, collectors, etc.) were imported from manufacturers in various countries, resulting in additional uncertainty over the EE calculations, as it is practically impossible to follow the production and delivery process for each component. The approach in this paper was to prepare an estimation of the EE based on the data from the previously reviewed references, complemented with data from ECOINVENT database [34].

An additional problem encountered was the difficulty in separating the EE for the DSWH from the EE of the auxiliary system providing hot water, as parts of the system would also be present if the solar system were not installed. For example, the whole EE value of the storage vessel cannot be attributed to the DSWH, as a smaller storage capacity would be in place even if the DSWH was not installed. The EE for each case was adjusted based on the experience of the authors to inference the potential systems that would be in place if DSWH were not present. The estimated EE values in this study are shown in Table 4.

Table 4
Calculation of EE for the different installations in MJ.

System ID	Pump	Cylinder capacity [a]	Glycol	Expansion vessel	Collectors	Copper piping	Total system components	Total[b] installation
No. 1	120	6000	440	300	7216	1400	15,476	18,571
No. 2	150	3000	600	400	9840	1400	15,390	18,468
No. 3	0	1000	200	0	3160	1050	5410	6492
No. 4	120	4000	420	300	6888	1400	13,128	15,754
No. 5	120	6000	300	300	6320	1050	14,090	16,908
No. 6	150	4000	810	500	13,284	1750	20,494	24,593

[a] Additional capacity required after installation of solar system.
[b] 20% margin has been added to the total calculated EE from the inventory analysis to account for transport, maintenance and disposal, as discussed in a sensitivity analysis by Ardente et al. [27].

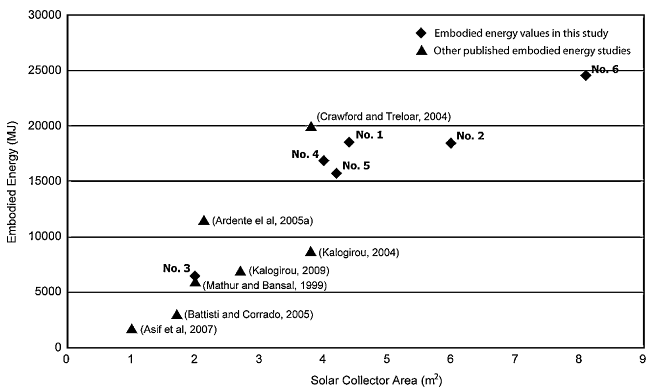


Fig. 8. Comparison of calculated EE data with previous studies.

Fig. 8 shows the calculated EE values, compared with the previously reviewed studies.

4.3. Energy payback

The 'energy payback' for the six installations was calculated as the number of years needed by each solar installation to save as much energy as its EE. The energy saved was calculated considering the efficiency of the auxiliary heating system to which the DSWH system is substituting, and applying a primary energy conversion factor depending the fuel used. The primary energy savings will therefore be higher if the auxiliary heating system displaced by the solar system is inefficient and/or has a high primary energy factor. For example in Ireland, where electricity for domestic use has a primary energy conversion factor of 2.7 [35], substitution of electric water heating by solar would yield the highest primary energy savings. When the substituted auxiliary heating is a more efficient system, such as a heat pump, the energy savings would be much smaller. For substitution of heat delivered from fossil fuels or wood, the primary energy factor (PEF) applied is 1.1 for the fuel, and the calculated energy savings will also depend on the efficiency of the boiler and heat delivery system.

The electricity used by the circulation pump of the solar system, when present, is deducted from the energy savings after applying a PEF for the electricity (2.7 for Ireland).

Eq. (1) shows the formula used for the calculation of energy savings in primary energy units, and Table 5 presents the calculation for each installation.

$$\text{Energy_Savings} = \frac{\text{Solar_Output} \times \text{PEF}_{\text{Aux.Heating}}}{\text{Efficiency}_{\text{Aux.Heating}}} - \frac{\text{Elec.Use.Pump}}{\text{PEF}_{\text{Elec}}} \quad (1)$$

Fig. 9 displays the energy payback based both on the predicted and measured performance of the DSWH systems, and compares it with previously reviewed publications. The energy payback in years is calculated using Eq. (2). It is assumed that the systems solar output and associated energy savings will remain the same every year.

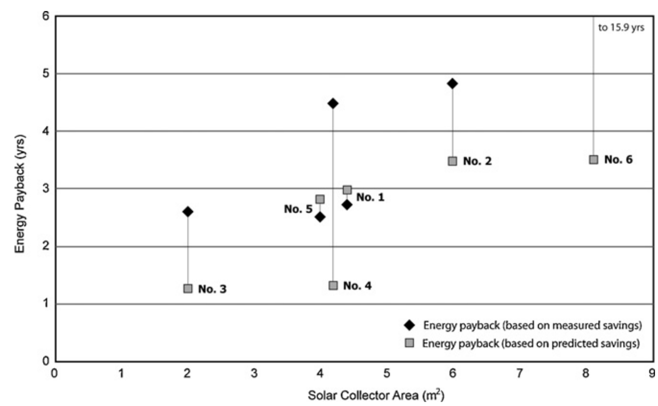


Fig. 9. Energy payback of the studied solar systems, based on predicted and measured energy savings.

$$\text{Energy_Payback} = \frac{\text{Embodied_Energy}}{\text{Annual_Energy_Savings}} \quad (2)$$

It can be observed that energy payback periods based on the predicted performance of the installations vary considerably depending of the type of installation and substituted auxiliary heating systems. The installations with shortest energy payback based on the expected performance of the installations correspond to installation No. 3 (1.2 years), which is a small thermoshypon system with just 2 m^2 of collection area, and to installation No. 4 (1.3 years), on which solar output substitutes a relatively inefficient auxiliary system of wood boiler and electric immersion. For the other four installations, energy paybacks based on predicted performance vary between 2.8 and 3.5 years. These energy payback periods are higher than previously reviewed studies which generally had energy payback periods between 0.5 and 2 years. However this difference can be considered reasonable considering the particular system and climate characteristics, as most of the previously reviewed studies were analyzing thermoshypon systems in sunnier climates.

For the cases where installations did not perform according to expectations, there are obviously considerable variations between the energy payback. Particularly noticeable is the high energy payback based on the real measured energy savings for installations No. 2, No. 4 and No. 6, which goes up to 4.9, 4.5 and 15.9 years, respectively.

4.4. Net Energy Ratio

The 'energy payback' has been included in this paper as it is the most frequently used indicator of the life cycle or net energy assessment of DSWH installations, as shown from the previously

Table 5
Auxiliary heating systems efficiency, primary energy factors for the fuels, and annual energy savings both for the expected and the measured performance.

System ID	Auxiliary heating	Primary energy conversion factor	Auxiliary system efficiency	Expected performance		Measured performance	
				Annual solar output (MJ)	Annual energy savings (MJ)	Annual solar output (MJ)	Annual energy savings (MJ)
No. 1	Condensing gas boiler	1.1	0.95	5903	6252	6402	6829
No. 2	Ground source heat pump	2.7	3	6585	5295	4932	3807
No. 3	Gas boiler	1.1	0.8	3778	5195	1811	2490
No. 4	Wood stove (50%) and electric immersion (50%)	Wood 1.1 Elec. 2.7	Wood 0.6–Elec. 1.0	5573	12,097	1777	3494
No. 5	Gas condensing boiler	1.1	0.95	5682	5996	6305	6717
No. 6	Ground source heat pump	2.7	3	8539	7005	2470	1543

reviewed studies. However, the Net Energy Ratio (NER), also frequently referred to as ‘energy return of energy invested’ (EROEI) or ‘energy return of investment’ (EROI), provides more accurate information of the life cycle energy performance of the systems, and can be directly compared with NER values for other renewable technologies [36]. The Net Energy Ratio of a DSWH system can be defined as the reduction of primary energy use due to the solar installation over its service life, divided by the installation EE. It can also be calculated as the service life divided by the energy payback (Eq. (3)). The NER has no units, and in plain terms represents ‘how many times’ the EE is saved by the system over its life cycle. A higher NER value represents a better life cycle energy performance.

$$\mathrm{NER} = \frac{\mathrm{Annual_Energy_Savings} \times \mathrm{Service_Life}}{\mathrm{Embodied_Energy}} = \frac{\mathrm{Service_Life}}{\mathrm{Energy_Payback}} \quad (3)$$

The service life of the installation is a key factor in the calculation of the Net Energy Ratio. A service life of between 15 and 25 years is a typical, as referenced in BS EN 15459 [37]. There are manufacturers who guarantee products up to 20 years, with some products expected to last longer than this. Base on this, the NER of the installations considered here has been calculated based on a 20 year service life. The results are presented in Table 6. As in the energy payback calculation, the solar energy output and associated energy savings have been considered constant for every year of the installations' service life.

The NER results can be compared with other on-site renewable energies such as photovoltaics (PV). For a typical on-site PV installation the EE can be estimated as 6120 MJ per square meter [38–41]. Its yearly energy savings in primary energy terms, calculated for Ireland and with typical efficiency factors from EN 15316 [42] would be 1094 MJ (112 kWh yearly electricity output per square meter, with a primary energy conversion factor of 2.7). Applying Eq. (3) to these values, assuming a service life of 25 years for the PV systems, the NER would equal 4.5.

It can be observed that the NER of DSWH systems based on expected systems performance is in all cases greater than the NER for PV systems, typically varying between 5.7 and 16. These results serve as a confirmation of the potential of DSWH to provide large life cycle energy savings. However it can also be observed that the NER based on the measured performance is substantially reduced for some of the installations, with system No. 2, No. 4 and No. 6 presenting NER values of 4.1, 4.3 and 1.7, respectively. These results are lower than the NER calculated for a PV system, highlighting the importance of correctly designing, installing, and operating DSWH systems to exploit the full benefits of the technology.

Table 6
Net Energy Ratio of the six installations, based on expected and measured performance.

System ID	Expected performance NER	Measured performance NER
No. 1	6.7	7.4
No. 2	5.7	4.1
No. 3	16.0	7.7
No. 4	15.4	4.4
No. 5	7.1	7.9
No. 6	5.7	1.3

5. Summary and conclusions

The potential of domestic solar water heating (DSWH) to reduce energy use for water heating is frequently acknowledged. However calculations of potential energy savings generally do not consider two factors that are of relative importance: firstly, a life cycle energy perspective, considering also the embodied energy (EE) of the systems, and secondly the real performance of the installation, which can be influenced by various design, installations, usage and operational factors. These can result in a very different performance to that predicted or expected from the systems.

A brief review of existing studies which considered EE of systems showed ‘energy payback’ periods generally in the range of 0.5–2 years, indicating that energy savings rapidly compensate for the EE of the DSWH systems. These studies have, however, been undertaken in regions with relatively high levels of solar irradiation and were based on energy performance estimates or expected energy savings. At the same time, a brief review of studies of the measured performance of DSWH systems has indicated that real energy savings can frequently be lower than expected energy savings.

This paper presented an analysis of the expected and measured performance of six DSWH installations in Ireland, typical of a western European maritime climate, and calculated the systems EE to provide a life cycle energy perspective.

The analysis demonstrated that when solar systems are properly sized, installed and operated, as is the case of installations No. 1 and No. 5, the performance is similar to expectations. The energy paybacks can be below 3 years, which is a good result when compared to previous studies and considering the differences in climate and installation typology. However, the measured energy savings of the DSWH installations in four of the six installations was lower than predicted. Particularly when the DSWH systems were oversized in relation to the hot water needs, or when combined with relatively efficient auxiliary heating systems such as ground source heat pumps, the measured performance of the installations was worse than predicted due to defects in the installation or control.

In terms of Net Energy Ratio (NER), values based on predicted performance vary between 5.7 and 16. These high values demonstrate how DSWH systems can be compared favourably, from a life

cycle energy perspective, to other on-site renewable energy technologies such as PV systems. However the defective performance of installations considerably lowers the NER value, showing that if the optimum performance for DSWH systems is not achieved, technologies such as PV systems would be a preferable option from a life cycle energy perspective.

The final conclusion is that for a correctly performing installation, the EE is generally a small portion of the life cycle energy savings, and energy paybacks as low as 3 years are possible even in a maritime climate such as Ireland. However DSWH system performance greatly depends on various factors such as hot water demand in the dwelling and the auxiliary heating system present. Although DSWH technology is well developed and relatively simple, measures have to be put in place to ensure appropriate design, installation and control, particularly in larger installations and when they are coupled with systems such as heat pumps. If systems fail to perform according to expectations, the EE becomes a much larger portion of the life cycle energy use, and the NER is reduced to values below other renewable energy technologies.

References

[1] EUROSTAT. Energy, transport and environment indicators; 2009.
[2] EuroACE. Towards energy efficient buildings in Europe; 2004.
[3] Denholm P. The technical potential of solar water heating to reduce fossil fuel use and greenhouse gas emissions in the United States. In: Technical Report NREL/TP-640-41157. National Renewable Energy Laboratory; 2007.
[4] Purohit P, Michaelowa A. CDM potential of solar water heating systems in India. Solar Energy 2008;82:799–811.
[5] Han J, Mol APJ, Lu Y. Solar water heaters in China: a new day dawning. Energy Policy 2010;38:383–91.
[6] AEE. Institute for sustainable technologies. Vienna University of Technology, Potential of Solar Thermal in Europe; 2009.
[7] TRNSYS. TRNSYS, transient systems simulation program; 2010. http://sel.me.wisc.edu/trnsys/.
[8] POLYSUN. POLYSUN, simulation software for solar thermal systems; 2010. http://www.solarconsulting.us/polysun.html.
[9] TSOL. TSOL, dynamic simulation programme for the design and optimisation of solar thermal systems; 2010. http://www.valentin.de/.
[10] CEN, BS EN 15316-4-3:2007. Heating systems in buildings – method for calculation of system energy requirements and system efficiencies – Part 4–3: heat generation systems, thermal solar systems; 2007.
[11] Cuadros F, López-Rodríguez F, Segador C, Marcos A. A simple procedure to size active solar heating schemes for low-energy building design. Energy and Buildings 2007;39:96–104.
[12] Raffenel Y, Fabrizio E, Virgone J, Blanco E, Filippi M. Integrated solar heating systems: from initial sizing procedure to dynamic simulation. Solar Energy 2009;83:657–63.
[13] Fraisse G, Bai Y, Le Pierrès N, Letz T. Comparative study of various optimization criteria for SDHWS and a suggestion for a new global evaluation. Solar Energy 2009;83:232–45.
[14] CEN, BS EN 12975-2:2006. Thermal solar systems and components. Solar collectors. Test methods; 2006.
[15] CEN, BS EN 12976-2:2006. Thermal solar systems components. Factory made systems. Test methods; 2006.
[16] International Organization for Standardization, ISO 9459-5: 2007. Solar heating – domestic water heating systems – Part 5: system performance characterization by means of whole-system tests and computer simulation; 2007.
[17] CEN, DD CEN/TS 12977-2:2010. Thermal solar systems and components – custom built systems – Part 2: test methods for solar water heaters and combisystems; 2010.
[18] Flamos A, Van der Gaast W, Doukas H, Deng G. EU and Asian countries policies and programmes for the diffusion of sustainable energy technologies. Asia Europe Journal 2008;6:261–76.
[19] Karagiorgas M, Botzios A, Tsoutsos T. Industrial solar thermal applications in Greece: economic evaluation, quality requirements and case studies. Renewable and Sustainable Energy Reviews 2001;5:157–73.
[20] Parker DS. Research highlights from a large scale residential monitoring study in a hot climate. Energy and Buildings 2003;35:863–76.
[21] Thomsen KE, Schultz JM, Poel B. Measured performance of 12 demonstration projects – IEA Task 13 advanced solar low energy buildings. Energy and Buildings 2005;37:111–9.
[22] Wall M. Energy-efficient terrace houses in Sweden: simulations and measurements. Energy and Buildings 2006;38:627–34.
[23] Lloyd CR, Kerr ASD. Performance of commercially available solar and heat pump water heaters. Energy Policy 2008;36:3807–13.
[24] C.L.A.R.C.T.E. Cleveland, Net energy analysis. In Cutler J (editor). Encyclopedia of Earth Cleveland (Washington, DC: Environmental Information Coalition, National Council for Science and the Environment). [First published in the Encyclopedia of Earth September 14, 2006; Last revised August 22, 2008; Retrieved August 30, 2009]. http://www.eoearth.org/article/Net_energy_analysis; 2008.
[25] Mathur J, Bansal N. Energy analysis of solar water heating systems in India. The International Journal of Life Cycle Assessment 1999;4:113–6.
[26] Crawford RH, Treloar GJ. Net energy analysis of solar and conventional domestic hot water systems in Melbourne, Australia. Solar Energy 2004;76:159–63.
[27] Ardente F, Beccali G, Cellura M, Lo Brano V. Life cycle assessment of a solar thermal collector. Renewable Energy 2005;30:1031–54.
[28] Kalogirou SA. Environmental benefits of domestic solar energy systems. Energy Conversion and Management 2004;45:3075–92.
[29] Kalogirou S. Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters. Solar Energy 2009;83:39–48.
[30] Battisti R, Corrado A. Environmental assessment of solar thermal collectors with integrated water storage. Journal of Cleaner Production 2005;13: 1295–300.
[31] Asif M, Currie J, Muneer T. Comparison of aluminium and stainless steel built-in-storage solar water heater. Building Services Engineering Research and Technology 2007;28:337–46.
[32] Meteotest, Meteonorm 6.1 Database, Available at www.meteonorm.com; 2010.
[33] Dixit MK, Fernández-Solís JL, Lavy S, Culp CH. Identification of parameters for embodied energy measurement: a literature review. Energy and Buildings 2010;42:1238–47.
[34] Swiss Centre for Life Cycle Inventories. ECOINVENT, life cycle inventory database; 2010. Available from http://www.ecoinvent.org/.
[35] Sustainable Energy Authority Ireland, Dwelling Energy Assessment Procedure (DEAP) – Irish official method for calculating and rating the energy performance of dwellings; 2007.
[36] Murphy DJ, Hall CAS. Year in review – EROI or energy return on (energy) invested. Annals of the New York Academy of Sciences 2010;1185:102–18.
[37] CEN, BS EN 15459:2007. Energy performance of buildings – economic evaluation procedure for energy systems in buildings; 2007.
[38] Pacca S, Sivaraman D, Keoleian GA. Parameters affecting the life cycle performance of PV technologies and systems. Energy Policy 2007;35: 3316–26.
[39] Nawaz I, Tiwari GN. Embodied energy analysis of photovoltaic (PV) system based on macro- and micro-level. Energy Policy 2006;34:3144–52.
[40] Raugei M, Bargigli S, Ulgiati S. Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si. Energy 2007;32:1310–8.
[41] Richards BS, Watt ME. Permanently dispelling a myth of photovoltaics via the adoption of a new net energy indicator. Renewable and Sustainable Energy Reviews 2007;11:162–72.
[42] CEN, BS EN 15316-4-6:2007. Heating systems in buildings – method for calculation of system energy requirements and system efficiencies – Part 4–6: heat generation systems, photovoltaic systems; 2007.
[43] European solar thermal industry federation, solar thermal markets in Europe – trends and market statistics 2009; 2010.
[44] McNicholl A, Lewis JO. Green design: sustainable building for Ireland, T.E.C.D.G.X.f.E. The Office of Public Works (Ed.); 1996.